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Line shape diagnostics of Galactic ^{26}Al

K. Kretschmer[1], R. Diehl[1], and D. H. Hartmann[2]

[1] Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany
[2] Department of Physics & Astronomy, Clemson University, Clemson, SC 29634-0978, USA

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Abstract. The shape of the gamma-ray line from radioactive ^{26}Al, at 1808.7 keV energy in the frame of the decaying isotope, is determined by its kinematics when it decays, typically 10^6 y after its ejection into the interstellar medium from its nucleosynthesis source. Three measurements of the line width exist: HEAO-C's 1982 value of $(0 + 3)$ keV FWHM, the GRIS 1996 value of (5.4 ± 1.3) keV FWHM, and the recent RHESSI value of (2.0 ± 0.8) keV FWHM, suggesting either "cold", "hot", or "warm" ^{26}Al in the ISM. We model the line width as expected from Galactic rotation, expanding supernova ejecta, and/or Wolf-Rayet winds, and predict a value below 1 keV (FWHM) with plausible assumptions about ^{26}Al initial velocities and expansion history. Even though the recent RHESSI measurement reduces the need to explain a broad line corresponding to 540 km s^{-1} mean ^{26}Al velocity through extreme assumptions about grain transport of ^{26}Al or huge interstellar cavities, our results suggest that standard ^{26}Al ejection models produce a line on the narrow side of what is observed by RHESSI and INTEGRAL. Improved INTEGRAL and RHESSI spatially-resolved line width measurements should help to disentangle the effects of Galactic rotation from the ISM trajectories of ^{26}Al.

Key words. nuclear reactions, nucleosynthesis, abundances – gamma rays: observations – supernovae: general – ISM: supernova remnants – stars: formation.

1. Introduction

Current Galactic nucleosynthesis reveals itself through the decay of ^{26}Al, one of its radioactive by-products with a mean lifetime of 1.04×10^6 y. ^{26}Al undergoes β^+-decay into an excited state of ^{26}Mg, which de-excites through emission of a gamma-ray photon at 1808.7 keV. This gamma-ray line has been observed and imaged throughout the Galaxy (Mahoney et al., 1982; Diehl et al., 1995; Oberlack, 1997; Knödlseder et al., 1999; Plüschke et al., 2001). Sources of ^{26}Al may be AGB stars and novae, but massive stars (via core-collapse supernovae and winds from Wolf-Rayet stars) have been found the most plausible and probably dominating sources (Prantzos & Diehl, 1996). The rather irregular ^{26}Al emission along the plane of the Galaxy, and its consistency with the patterns of tracers of massive-star activity, is the main argument for favouring massive stars as the sources (Diehl et al., 1996; Knödlseder et al., 1999; Plüschke et al., 2001). Flux measurements have been employed to study the nature of the sources, comparing with predicted ^{26}Al yields from models of the source types. The amount of ^{26}Al present in the ISM of the Galaxy has been estimated at ≈ 2 M$_\odot$, and used to argue for the roles of different source types. But the uncertainties about the spatial distribution and total number of nucleosynthesis events add to source yield uncertainties, providing only qualitative arguments for the nature of ^{26}Al sources (Prantzos & Diehl, 1996). Therefore, locally constrained candidate source populations have been studied, such as in the Cygnus region (Knödlseder et al., 2000; Plüschke et al., 2001). In such a case, the distance to the sources is constrained to a smaller interval, along with the radial velocity due to Galactic rotation.

Measurements of Galactic ^{26}Al with high-resolution spectrometers have produced somewhat controversial results: The initial discovery with the space-borne HEAO-C Ge spectrometer had reported a narrow line (intrinsic width (FWHM) (0 + 3) keV; Mahoney et al., 1984). But the GRIS balloon-borne Ge spectrometer found the line to be significantly broadened (intrinsic FWHM (5.4 ± 1.4) keV; Naya et al. (1996)). Such a broad line, however, cannot be explained easily (see Chen et al., 1997). If the origin of the line broadening was thermal, the ^{26}Al decay region would need to be at a temperature of $\approx 4.5 \times 10^8$ K. Alternatively, ^{26}Al isotopes would have to maintain a mean velocity around 540 km s^{-1} over their 1 My decay time, travelling kpc distances at those speeds. One may either assume that a substantial fraction of ^{26}Al is injected into such rather large interstellar cavities, or that a substantial fraction of ^{26}Al condenses onto dust grains before deceleration, so it maintains its momentum throughout passages of supernova remnant shells or other obstacles. The velocity could also be a result of re-acceleration of dust grains by interstellar shocks in the neighbourhood of the source, allowing them to maintain a high velocity over the ^{26}Al decay time scale (Sturner & Naya, 1999). None of these explanations is straightforward or without prob-

Send offprint requests to: K. Kretschmer, e-mail: kkr@mpe.mpg.de

lems. A firm measurement of the ^{26}Al gamma-ray line width is desirable, before questioning our understanding of ^{26}Al fate from its production sites until decay in interstellar space.

New measurements have been obtained recently with Ge spectrometers aboard the high energy solar spectroscopy imager RHESSI (Smith, 2003) and the INTEGRAL observatory. The RHESSI result was derived through Earth occultation analysis of data while pointing at the sun. They obtain an intermediate intrinsic line width of about (2.0 ± 0.8) keV FWHM. The preliminary INTEGRAL measurement also suggests a narrow line, but systematic uncertainties are still large (Diehl et al., 2003). Within the given uncertainties, the current set of measurements is mildly inconsistent. But more measurements have been recorded with INTEGRAL's SPI Ge spectrometer already, so that longitude-resolved line width results are at the horizon.

We explore the potential of ^{26}Al decay line shape measurements for diagnostics on the sources of ^{26}Al and their interstellar environment. We follow up on earlier analysis by Gehrels & Chen (1996), who showed that the structure of the Galaxy should be reflected in the position of the line due to Doppler shift from Galactic rotation. In this paper we employ an updated spatial distribution model for the plausible sources of ^{26}Al in the Galaxy. We also account for the fate of ejected ^{26}Al in interstellar space through different model variants which reflect ejections by winds and/or supernovae into cavities of plausible sizes for the massive-star environment of the ^{26}Al sources. Our aim is to illustrate the diagnostic power of measuring the ^{26}Al gamma-ray line's position and width; this should be feasible with current instrumentation through imaging spectroscopy, even if a detailed decomposition of the line shape may still be beyond reach.

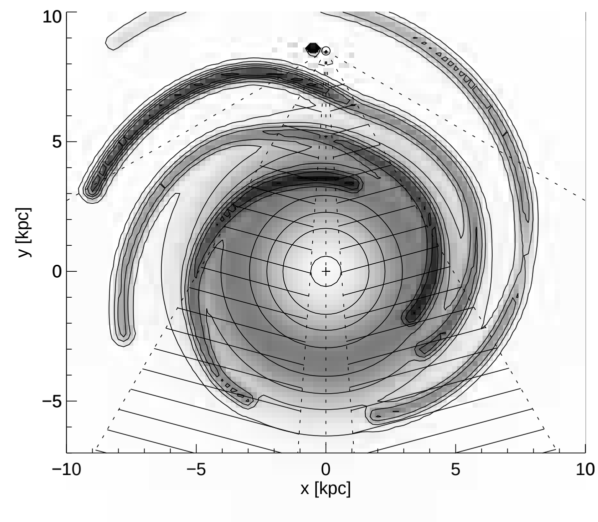

Fig. 1. Model of the free electron density in the galactic plane (Taylor & Cordes, 1993), used as ^{26}Al source density distribution. Dotted lines represent −60°, −30°, −4°, 0°, 4°, 30°and 60° galactic longitude. Hatched areas illustrate the eastern/western parts of the inner galactic region.

2. ^{26}Al Sources in the Galaxy

Our model for the distribution of ^{26}Al in the Galaxy is based on two separate aspects: the distribution of nucleosynthesis events in the Galaxy, and the distribution of ^{26}Al in interstellar space following an individual nucleosynthesis event. For each of these, spatial as well as velocity-space densities have to be considered.

The angular distribution of ^{26}Al 1809 keV emission on the sky correlates well with tracers of ionisation, such as H_α or free-free emission. Therefore we adopt a three-dimensional model for the space density of free electrons as our parent distribution for ^{26}Al sources in the Galaxy. Such a model has been derived by Taylor & Cordes (1993) from pulsar dispersion measure observations (a cut through this model along the Galactic plane can be seen in Fig. **??**); it was updated in Cordes & Lazio (2002). Alternative spatial models, such as the smooth, axisymmetric one by Gómez et al. (2001) will probably yield similar line shape results.

The Doppler shifts due to Galactic rotation can then be determined from the Galactic rotation curve. For our model we used the results obtained by Olling & Merrifield (2000) from fitting radial velocity measurements with a five-component mass model of the Galaxy, consisting of a stellar bulge, a stellar disc, two gas discs (H I, H_2) and a dark-matter halo. Because their determination of the rotation curve depends on the values of the distance to the galactic centre R_0 and the local circular speed Θ_0, which are not known to a high degree of precision, they allowed these parameters to vary over a broad range of values. In view of these uncertainties and because we are interested mainly in the inner Galaxy, we approximated the rotation curve given by Olling & Merrifield for the IAU standard values $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1} with the radial dependence:

$$|\boldsymbol{v}|(R) = 220 \text{ km s}^{-1} \cdot [1 - \exp(-R/1 \text{ kpc})]$$

the velocity vector being parallel to the plane and perpendicular to the vector pointing from the galactic centre to the source location.

Superimposed on Galactic rotation is the motion of freshly synthesised radioactive material due to the parental supernova explosion or the ejecting Wolf-Rayet star wind and its slowed-down motion in the ISM before decay, i.e. within $\approx 10^6$ yr. Concentrating first on supernovae, we adopt a particular expansion behaviour: Recent hydrodynamic simulations of type II supernovae by Kifonidis et al. (2003) find that the expansion of the bulk of nucleosynthetic SN products such as ^{26}Al may be at velocities less than 1200 km s^{-1}. To reflect their results, we allow ^{26}Al to expand freely with a velocity of 1500 km s^{-1} until it reaches the radius of the SN reverse shock formed by circumstellar interaction. After this point, we expand ^{26}Al at the velocity of the blast wave shock; this gives us a conservative estimate because ^{26}Al is likely to move slower than the forward shock. For our model of SNR dynamics from circumstellar interaction, we adopt the values for Kepler's supernova remnant shock positions and velocities given by McKee & Truelove (1995).

At present, our model does not include other ^{26}Al sources; Type Ib/Ic supernovae and Wolf-Rayet stars (Prantzos & Diehl, 1996), which eject matter at similar or even higher speeds than Type II SNe (Mellema & Lundqvist, 2002; Prinja et al., 1990; Garcia-Segura et al., 1996). Also, the interaction of ejected

matter with the surrounding medium depends on the star formation history of the source region, where bubbles forming around groups of young massive stars play a potentially large role. Cavities extending over several hundred pc have been observed in galaxies (Oey & Clarke, 1996), and the Eridanus cavity (Burrows et al., 1993) presents us with a nearby example of such a cavity, extending from the Orion star forming region to very near the Sun. Matter ejected into such a low-density bubble could expand almost freely until reaching the boundary whereas typically assumed ISM densities ($n_{\rm H} \simeq 1$ cm^{-3}) would slow it down quite rapidly. To keep the model simple at first, we adopt above SNR model as typical for ^{26}Al sources; refinements will be discussed in our subsequent studies.

With these assumptions, the ejected ^{26}Al moves freely for $\approx$ 2 kyr, then decelerates with the SNR's shell. The shell reaches a radius where it dissolves in the ISM at an age comparable to the lifetime of ^{26}Al , when a significant fraction has therefore already decayed. We note that the expansion velocity drops below the characteristic rotational velocity of 220 km s^{-1} at $\approx$ 40 kyr, when 96% of the ^{26}Al is still left. Therefore the contribution from expansion to the overall line width will be rather small in our model.

3. Line Shape Diagnostics

We obtain simulated sky maps and spectra from a Monte Carlo scheme: ^{26}Al source locations are chosen randomly from a spatial distribution proportional to the free electron density, distributing candidate source positions within a volume centered on the Galaxy and extending 25 kpc in the plane and 7.5 kpc perpendicular to the plane. The free-electron density within this volume is taken from Taylor & Cordes (1993). For each nucleosynthesis event, a random age is chosen within the interval $[0, 10^7$ yr$]$. From this we evaluate the intrinsic velocity distribution and size of the ^{26}Al source, following the above expansion model. The age of the nucleosynthesis event thus determines extent and intrinsic velocity of its ejecta, as well as their 1.809 MeV luminosity. We represent each event by 2^{10} mass elements to reflect its spatial extent.

With the observer at $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}, we obtain viewing direction and radial velocity of ^{26}Al sources. Direction and radial velocity give us the coordinates of the ^{26}Al source mass element in a data space of ^{26}Al decay luminosity as a function of longitude, latitude and photon energy.

Projecting this data volume onto the longitude-energy plane, we obtain a map of ^{26}Al line intensities as a function of Galactic longitude and observed photon energy (See Fig. **??**). The intrinsic velocity spreads and spatial source distributions lead to a line blurring of $\approx 0.3 - 0.5$ keV along the plane of the Galaxy. Galactic rotation leads to the symmetric line shifts east and west of the Galactic centre. Deviating from the trend of decreasing surface brightness with increasing separation from the Galactic centre, we notice a prominent flux enhancement around $-70°$, which corresponds to the direction tangential to the Carina-Sagittarius spiral arm, which is also clearly visible in the longitude profile of our source distribution model, superimposed as a histogram in the upper half of the figure; see also Fig. **??**.

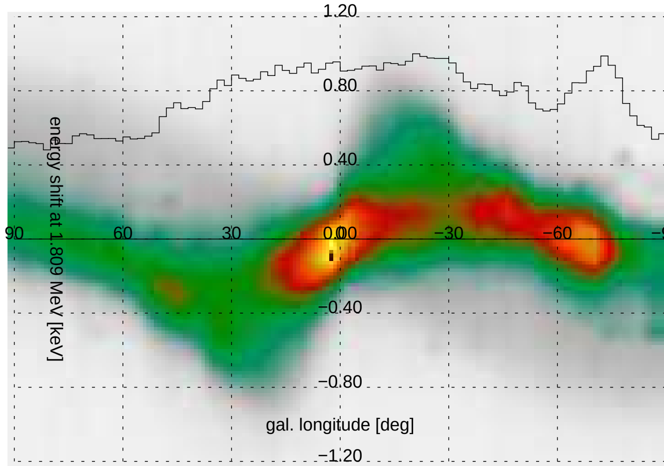

Fig. 2. ^{26}Al line intensity as a function of Galactic longitude and gamma-ray photon energy, with the source longitude profile superimposed

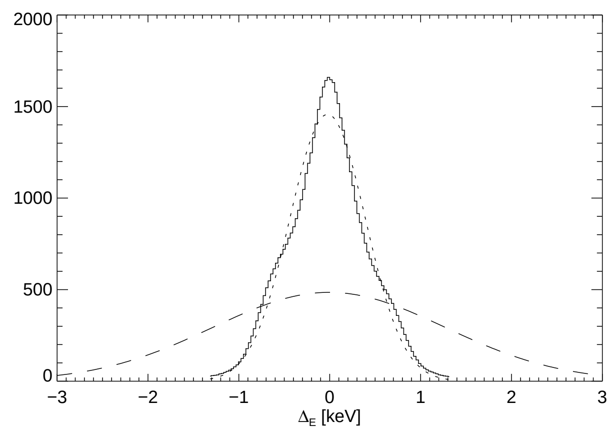

Fig. 3. Spectrum of the inner galaxy ($l \in [-30°, 30°]$. The full line is the source spectrum, the dotted line the best-fitting Gaussian, and the dashed line results from a convolution with a 2.8 keV FWHM Gaussian adopted for instrumental resolution of the measuring detector. $b \in [-5°, 5°]$)

In order to compare with a measured line profile, we integrate our simulated skymap of line energies and intensities over a region of interest of and obtain a resulting spectrum corresponding to an observation of this region without spatial, but with perfect spectral resolution. The spectrum shown in Fig. **??** represents a region-of-interest chosen to reflect the RHESSI analysis of the inner Galaxy (Smith, 2003). Fitting a Gaussian to this spectrum yields an equivalent line width of 1.0 keV (FWHM). The deviation from a Gaussian shape, which appears clear in our model spectrum (Fig. **??**, continuous line versus dotted line) is probably too small to be detectable with a realistic Ge detector of instrumental resolution 2.8 keV FWHM (approximate for SPI on INTEGRAL, determined by in-orbit measurements of detector background lines; Attié et al., 2003), convolution with the instrument response suppresses the difference between the measured flux and a Gaussian by a factor of $\approx$ 2000 (see dashed line in Fig. **??**).

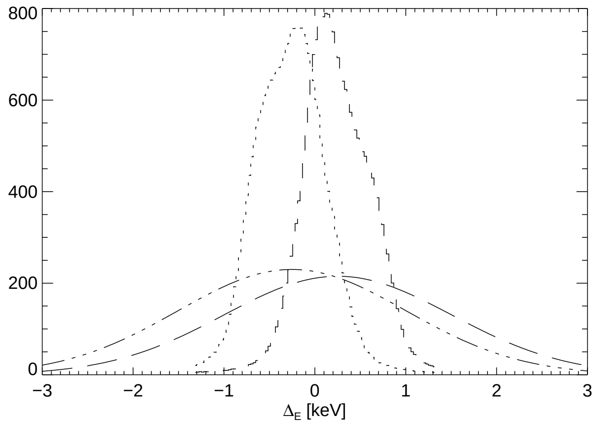

Fig. 4. Illustrations of lines from different Galactic regions: The histograms (dotted/dashed lines) show the spectra of the eastern/western part of the inner galactic region (i.e. $\pm 5°$ in latitude, $\pm[4° - 30°]$ in longitude) Energy-resolution limited spectra (obtained by convolving with 2.8 keV FWHM Gaussians) are shown as dash-dotted/long-dashed lines.

Nevertheless, spatially resolved observations can – at least partially – separate the rotational effect from the total line broadening. Fig. **??** compares the model spectra of the east and west part of the inner galactic region. (defined by $b \in [-5°, 5°]$ and $l \in [4°, 30°]$, $l \in [-30°, -4°]$, respectively) If we assume an instrument with a spectral resolution of 2.8 keV FWHM, the observed spectra are again almost indistinguishable from Gaussians, but we expect their centroids to be shifted by a significant energy offset. For our choice of parameters, she shifts amount to −0.25 keV for the eastern and +0.25 keV for the western part. A real measurement would yield a line width that is lower than the width obtained for the entire inner Galaxy. When we fit Gaussians to these resolution-limited spectra, we obtain $\approx$ 0.9 keV, compared to $\approx$ 1.0 keV for the whole inner region ($b \in [-5°, 5°]$, $l \in [-30°, 30°]$, Fig. **??**). This is due to the fact that partial-region spectra only include a lower dynamic range of velocities.

We used data analysis parameters from the first inner-Galaxy observations of INTEGRAL's core programme to estimate the possible precision of gamma-ray line centroid measurements. By using Gaussian fits to simulated spectra with varying levels of statistical noise, we tested the relation of the achievable line position determination accuracy and the signal-to-noise ratio. We confirm the centroid uncertainty to be proportional to the noise-to-signal ratio, therefore scaling with the inverse square root of exposure time. At present, noise is dominated by systematic uncertainties, resulting in a position uncertainty of ±0.19 keV. If we extrapolate to the full exposure of 3 Ms scheduled for the first year of INTEGRAL operations, we estimate a statistical uncertainty for the ^{26}Al line centroid of ±0.06 keV. We expect that systematic uncertainties in INTEGRAL results can be reduced in the near future through studies of SPI's spectral resolution, energy calibration stability, and background in-flight behaviour. When systematic uncertainties are reduced below the level of statistical uncertainty, we expect a 3σ detection of the Doppler shift relative to an equally long observation at the Galactic longitude of maximum Doppler shift at $l = 330°$.

4. Conclusions

We model ^{26}Al sources in the Galaxy, adopting massive stars as the dominating sources. Using Galactic rotation and plausible assumptions for the fate of ^{26}Al from ejection by the supernova or Wolf Rayet star into until decay in interstellar space, we derive an expected profile for the 1809 keV gamma-ray line from the decay of Galactic ^{26}Al. For this, we integrate along the lines of sight over the Doppler-shifted source regions of ^{26}Al emission with their intrinsic state of dynamical evolution.

Measurements of the 1809 keV emission from galactic ^{26}Al play in principle a role similar to the H I 21 cm radiation, with the benefit that the Galaxy is always optically thin to MeV gamma radiation. Current instruments are unable to improve the knowledge of galactic rotation over H I results, the basis for the inner galaxy rotation curve by Olling & Merrifield (2000), but the knowledge of rotation can be used to test the position of ^{26}Al sources.

Our result demonstrates that the gamma-ray line profile reflects the kinematics of decaying ^{26}Al in the ISM. However, current Ge detectors will probably be unable to detect line shape departures from a simple Gaussian shape for spectra such as predicted by our model. Nevertheless, centroid and width of the line will provide a diagnostic for the ^{26}Al sources in the Galaxy.

Detection of the expected amount of line shift would put a limit on the contribution of local emission to the ^{26}Al flux in the direction of the inner galaxy. By their massive star origin, ^{26}Al and H II-regions are connected; the latter having also been used to measure galactic rotation (Brand & Blitz , 1993). H II regions are created by the ionising radiation from O stars, therefore probe the first 2 My of star formation. The peak of ^{26}Al emission from a coeval group of massive stars only begins at 2 My, continuing for another 10 My (Plüschke et al., 2001). This demonstrates that ^{26}Al and the other analyses of galactic rotation may complement each other.

Our model parameters, chosen to represent supernova-produced ^{26}Al with ejection into an typical ISM environment, predict a line width of $\approx$ 1 keV for the inner Galaxy. This value is on the low side of the recent RHESSI measurement (Smith, 2003), and significantly below the "broad" line reported from the GRIS balloon measurement (Naya et al., 1996). We suggest, therefore, that ^{26}Al decay in the interstellar medium is likely to teach us more about the ejection and expansion characteristics of nucleosynthesis ejecta, and thus about the morphology of the interstellar medium in the vicinity of massive stars, our assumed sources of ^{26}Al in the Galaxy. For example, if ^{26}Al sources typically are surrounded by cavities from earlier massive-star action, this could lead to some additional broadening of the observed ^{26}Al gamma-ray line. Further imaging spectroscopy analysis of RHESSI data and of measurements with the SPI Ge spectrometer on INTEGRAL (launched in October 2002; Winkler et al., 2003) promise to provide the data for such studies.

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